Renewable and Sustainable Energy Reviews 16 (2012) 2558–2565

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The role of pumped storage systems towards the large scale wind integration in the Greek power supply system

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ARTICLE INFO

Article history:
Received 29 April 2011
Accepted 29 January 2012
Available online 20 March 2012

Keywords:
Pumped storage systems
Greek power system
Large wind integration
Tariffs

ABSTRACT

In the recent years, the debate on the necessity of pumped storage systems in the Greek power supply system has started. In the current decade, the Greek power system will gradually try higher RES penetration, mainly due to wind energy and photovoltaics integration. Variability of wind and PV generation and the current structure of the Greek power system introduce technical constraints, which should be taken into consideration in the forthcoming large scale RES integration. This paper examines the ability of the Greek power system to absorb renewable power and the necessity of pumped storage systems. The feasibility of pumped storage systems is discussed in three different scenarios of wind–photovoltaics integration. Results show that for the gradual increase of variable output RES, pumped storage systems are required, but the feasibility of pumped storage systems is not proved in the intermediate scenarios of RES integration.

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1. Introduction

Wind energy represents a rapid growth worldwide and is the most commercially and economically competitive renewable energy source. Several power systems in the world are supplied and will be supplied in the near future by large fractions of wind energy. As regards the wind share at a national level, Denmark, Spain and Portugal are leaders with 24%, 14.4% and 14% of annual contribution respectively [1]. Denmark achieves this rate, thanks to the large interconnections with other major European grids, while Portugal, due to the parallel operation of several hydroelectric stations. The autonomous power system of Crete represents a 14% annual wind energy contribution which could be considered as an upper technical limit in such cases [2].

In Greece, the achievement of national targets will be based primary on wind farms development, and secondarily on photovoltaics, because the former is considered as a more mature, efficient and economic technology in relation to the latter. Despite their high cost, photovoltaics contribute in the summer midday peak demand, and provide the power system with beneficiary distributed generation very close to the consumption. The national target for the penetration of RES is set at 40% of gross electricity consumption by 2020 [3]. According to the national action plan [4] the achievement of this target will be reached with 7500 MW of

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doi:10.1016/j.rser.2012.01.068

wind installed capacity and at least 2200 MW photovoltaics. This constitutes a very high RES penetration degree, which excess the current international experience and requires special management and innovative technical and regulatory solutions. The Greek power system is characterized by large lignite-fired units' contribution, by limited interconnections with the rest of Europe, and a rather limited capacity of hydroelectric plants.

2. Current situation and prospects

In the Greek power system of the mainland, the cumulative capacity of conventional and hydro power units is 11,234.3 MW, according to official figures of the Hellenic Transmission System Operator (HTSO). The electrical system of the mainland consists of 33 conventional units, of which 22 lignite (5288 MW), 4 oil (750 MW), 4 combined cycle units (1630 MW), 3 units of natural gas (507.8 MW), and several hydroelectric plants (3058.5 MW). Hydro plants have an annual contribution of 5 TW h in a typical hydraulic year, and definitely are used for peak supply.

In the current work, except of the "current status" scenario with 1000 MW wind and 100 MW PV capacity, three scenarios of wind–PV penetration are examined (3000–500, 5000–1000 and 8000–2000 MW). The optimum locations for the wind capacity is achieved by the results of a parallel work [5] and are presented in Fig. 1. This sitting has been achieved by the use of an optimization genetic algorithm aiming at the most effective integration of wind energy in the Greek territory, and adopting the gradual islands' wind potential exploitation via their interconnections with the mainland.

As reference year in the current work is considered a typical year with annual electricity demand 60 TW h, and peak demand 11.0 GW. The analysis is based on hourly demand time series of 2006 (with recorded annual energy and peak demand 49 TW h and 10.3 GW), after appropriate conversion to meet the reference year. Annual data of 2006 are used, as long as simultaneous time series of wind velocity across the whole territory are available for the same year. These wind time-series have been reproduced by systematic application of a mesoscale weather prediction model [6,7]. Next, for a desirable wind power installed capacity at each area and using a representative wind turbine power curve, hourly time series of the cumulative available wind power production can be reproduced on an annual basis. By this way probable correlation between wind power production and load demand are taking into consideration. In Fig. 2, annual time series of demand and electricity generation from wind and solar, and their respective duration curves are presented.

3. Simulation of the Greek power supply system

3.1. Basic concept

The aim of the current approach is to estimate the electricity production from renewable energy sources that can be absorbed directly from the Greek power system. RES power absorption or equivalently its complement RES power curtailment, is an important issue which should be taken into consideration, as soon as affects directly the renewable electricity supply. For this purpose the Greek power system is simulated.

The methodology examines the steady-state operation of the Greek power system and takes into account the specific characteristics of demand, the technical features of conventional and hydro power plants and the technical constraints for the smooth and safe operation of the system. For the application of this methodology, the units' commitment and load dispatch should be first clarified. In the perspective of the gradual increase of renewable energy sources in the Greek power system, it is clear that management rules and operational principles will differ from the current practice.

First of all as regards the management of variable production renewable energy technologies, wind power curtailment may occur and could be established through a central control system by the Hellenic Transmission System Operator, as it has been already established in the autonomous Greek islands. On the contrary, curtailment of photovoltaics power cannot be so easily occurred due to distributed generation by many small units and the absence of the required controllers. Over and above, electricity production with Photovoltaics, always very close to the demand and predictable, is – up to now – too expensive type of energy to be curtailed and should be absorbed in priority.

Technical constraints regarding the commitment, the load dispatch and the safe operation of the system are considered. Conventional units cannot be charged under their technical minimums. For lignite-fired units, this limit is considered at least 70% of their nominal power. While, for gas-turbines and diesel generators this limit is 30% of their nominal power.

It is assumed that wind and load forecast models are systematically used by the Transmission System Operator. Then load demand, wind and PV power availability and variability are considered sufficiently predictable. In this model, the power dispatch and the schedule of conventional power stations are defined, recognizing two main categories of conventional units; base load units and peak load units. The former concerns heavy lignite power units and the latter gas turbines and diesel power units. The number of base load units to be committed is defined by the expected low demand of the next 15 days.

Peak load units are characterized by their ability to provide quick response and to undertake the variability of demand and RES production. Then, a first approach of the number of peak demand units to be committed is related to the expected variability of demand and RES power generation for the hours ahead. This means that if high variability of load demand and RES generation is expected for the hours ahead, more flexible peak load units are required to be committed to ensure the safe operation of the power system.

A special methodological treatment is considered for hydropower. Today, in Greece, hydro plants operate during peak hours which always occur in summer. In the near future, their generation should be properly adjusted not only with peak demand, but also with the variability of rest RES power generation. Wind power curtailment may occur in low demand or in windy periods. During low demand hours hydro power plants are switched off. During peak demand periods, if there is wind power surplus, hydro power plants may reduce their operation saving water for peak demand periods of low wind. So, wind power plants could save water in the hydro plants' reservoirs and hydro generation will not constrain wind power absorption.

In order to have results in the safe side, a dynamic limit related with the permitted instantaneous penetration of wind power is considered to ensure the stability of the system in emergency case. For example a sudden fall of wind or a sudden storm over all the wind power plants, could lead in total loss of wind generation. Although such cases are considered improbable to occur, this dynamic limit ensures that other units, already committed, will be able to increase their production before the system collapse. In this analysis the base value of the allowed instantaneous wind power is set to 60% of the load demand.

Load demand, wind and photovoltaics generation are taken into consideration through the annual time series. Especially the time series of wind production has been derived using wind speed time series reproduced by a meso-scale weather forecast model systematically applied in the whole country. Thus, given the installed wind power in every region and representative power curve, the output of wind power is calculated. Aggregating the output of wind power

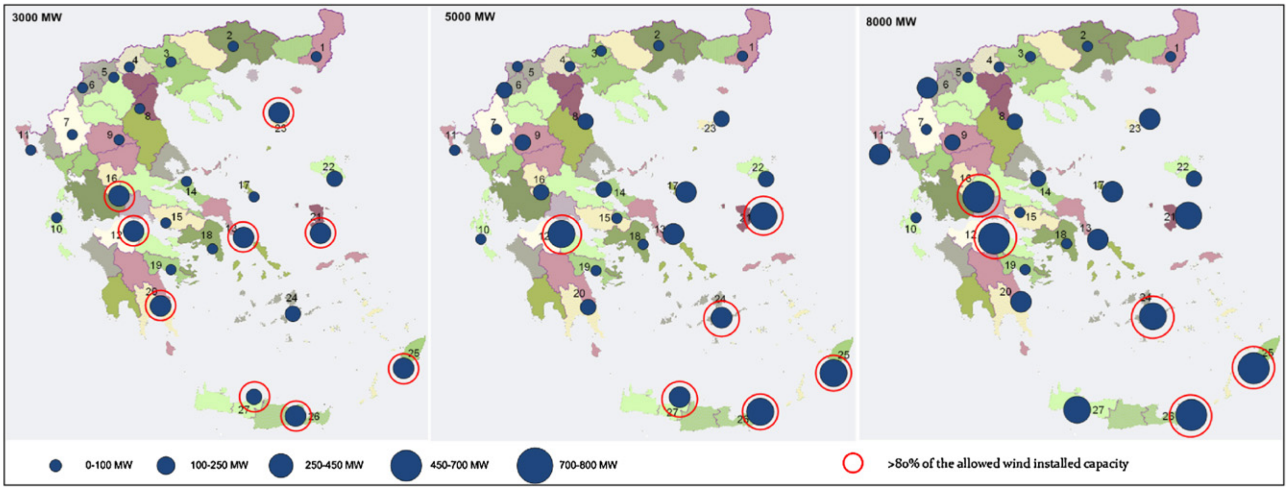

Fig. 1. Indicative sitting for 3000, 5000 and 8000 MW wind installed capacity [5].

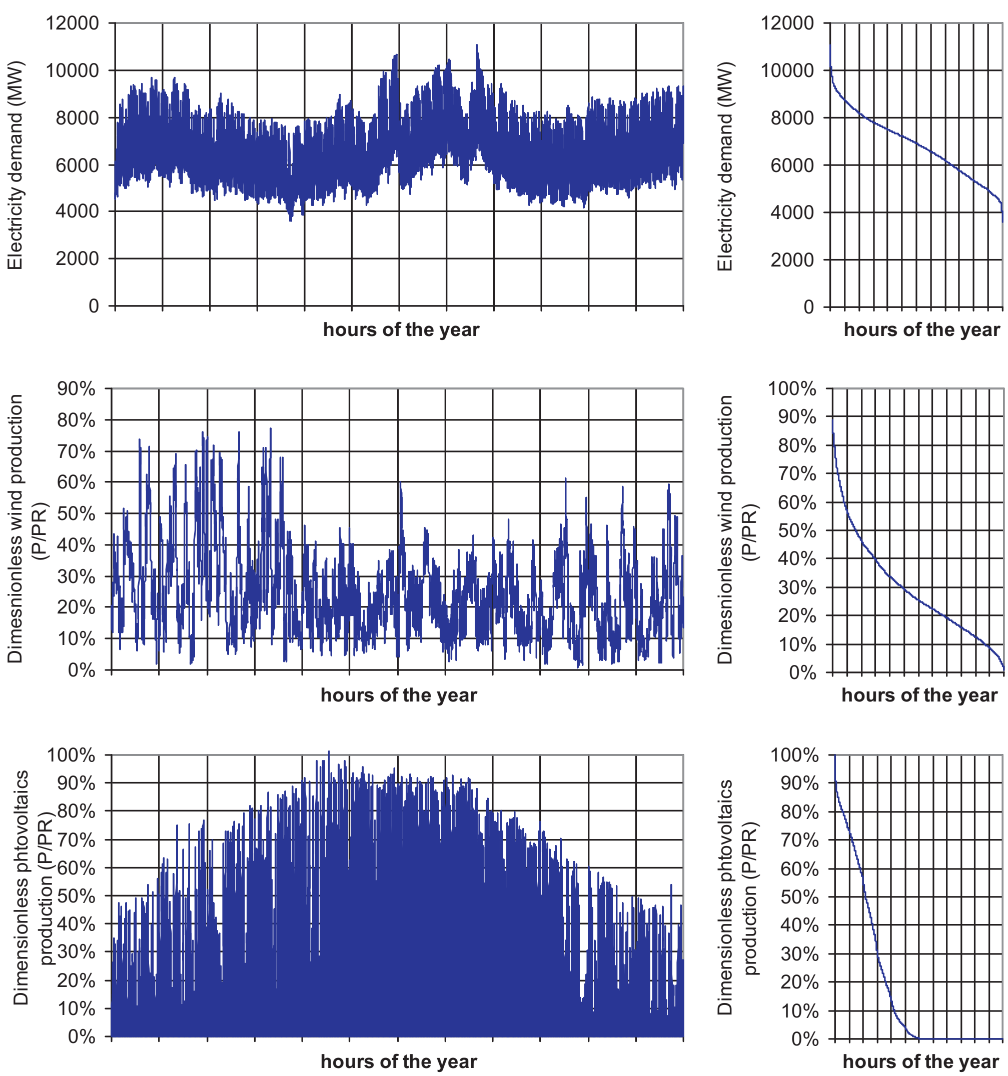

Fig. 2. Annual time series and duration curves: (a) of electricity demand, (b) of wind production (c) of PV production.

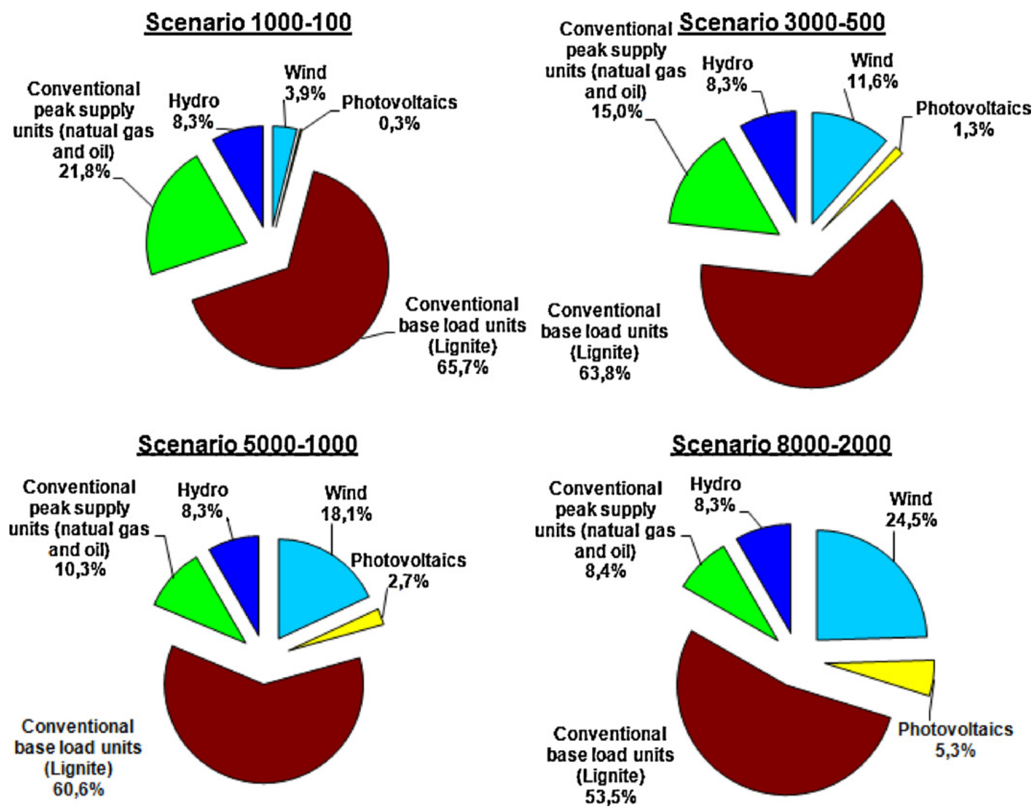

Fig. 3. Energy mix for four scenarios of wind–PV integration in reference year (energy demand 60 TW h and peak demand 11,000 MW): (a) 1000–100, (b) 3000–500, (c) 5000–1000, (d) 8000–2000.

in all the different regions, the total available wind power for every time "window" (e.g. an hour) is derived.

The interconnections of Greece with neighboring countries have a rather small capacity, while until today the priority of such interconnections is not the cross-border transmission of wind generation. Additionally, neighbors with lower energy demand and similar load profile may not be able to absorb energy surplus. Therefore, Greek system is treated as a rather isolated power system.

The methodology calculates the ability of the Greek system to absorb wind energy on an annual basis. For each time step, the definition of wind power curtailment among all the wind farms depends on their production and the needs of the power system. Then, larger annual curtailment may occur in areas with hyper accumulation of wind farms, and lower in areas with lower concentration and uncorrelated wind.

Finally, the methodology provides results about the annual energy mix, the renewable energy contribution and annual distribution of wind power curtailment.

4. Results

In this paragraph the results from the application of the above described methodology in four scenarios are presented. The four scenarios for wind–photovoltaics capacity are:

- 1000 MW–100 MW (current situation).
- 3000 MW–500 MW.
- 5000 MW–1000 MW.
- 8000 MW–2000 MW.

In Fig. 3, the annual energy mix is presented for the four examined scenarios. RES supply gradually is increased, while the operation of base load and peak supply conventional units is decreased. Analytically, the share of lignite is expected to gradually be decreased from 65.7% in the current situation, to 53.5% in the scenario 8000–2000 MW. Respectively, the share of peak supply conventional units is decreased from 21.8% today to 8.4%. Although the annual share of peak supply conventional units is decreased, the required installed capacity of peak supply units remains stable or is increased. This means that with large scale RES integration, more flexible power units are required, to maintain the same level of safety of the power system.

Besides all these flexible power units, wind energy curtailment is gradually increased. In Fig. 4, duration curves of wind power surplus are presented for the three scenarios of wind–PV integration. For the three examined scenarios results are summarized:

- For the "3000–500 MW", wind power surplus occurs annually for 188 h, wind energy surplus is 0.072 TW h, or the 1% of the annual wind power generation.

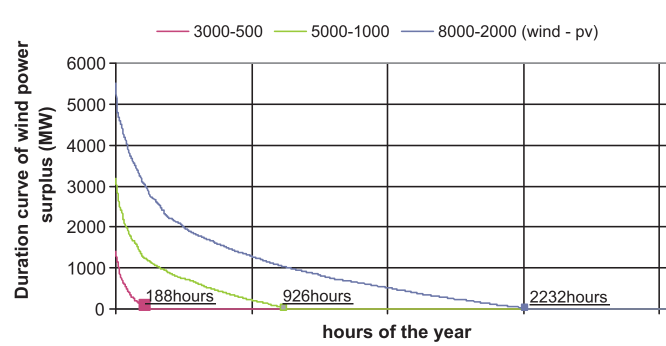

Fig. 4. Duration curve of wind power surplus for the three examined scenarios of wind–PV integration: 3000–500, 5000–1000 and 8000–2000 MW.

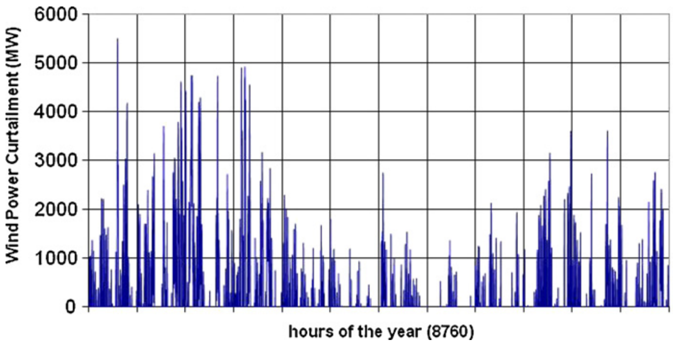

Fig. 5. Annual distribution of wind energy surplus for the scenario of 8000 MW wind–2000 MW PV integration.

- For the "5000–1000 MW", wind power surplus occurs annually for 926 h, wind energy surplus is 0.685 TW h, or the 5.9% of the annual wind power generation.
- For the "8000–2000 MW", wind power surplus occurs annually for 2232 h, wind energy surplus is 2.5 TW h, or the 14.5% of the annual wind power generation.

The hour annual distribution of the wind power surplus is presented in Fig. 5, for the last scenario. According to this figure, about 55–60 sequential cycles of wind power surplus occur, indicating the required cycle of probable pumped storage units. Additionally, it is obvious that there is a lack of wind power surplus, during summer months, due to high load demand.

Duration curve of wind power surplus represents a high slope, which means that high wind power surplus is available for few hours annually, while there are large periods without wind power surplus.

5. Exploitation of wind energy surplus in pumped storage systems

5.1. Basic principles

In this second stage of this work, the exploitation of wind energy surplus in pumped storage systems is examined. For this purpose the main energy amounts and the feasibility of these plants are analysed.

Pumped storage represents several advantages and is considered as the most suitable solution for energy storage; large amounts of energy can be stored, energy is recovered fast with high efficiency and a mature and reliable technology is implemented. The application can use one of the existing water reservoirs and an upper reservoir will be formed by dam or reservoir of a rather low capacity sufficient for at least 2 or 3 days cycle operation. Another important feature is that the conversion of stored energy into electrical energy is done effectively and efficiently through hydro turbines. Pumped storage is a mature technology, which is applied at least for the last 80 years. In the past, large pumped storage systems were scheduled for pumping operation during hours of low demand, using reverse hydro machines and storing excess energy of thermal power plants.

The operation of pumped storage to store wind energy surplus compared to the projects that store the excess energy of thermal power stations differ due to the lower predictability of the timing, duration and amount of wind energy surplus. The basic operating principles of hydro pumped storage systems have been described in detail in previous works [8,9].

In the energy storage phase, the wind energy surplus is converted to hydraulic through the process of pumping water from a lower reservoir to an upper reservoir with a height difference *h*. For the recovering phase, there is a movement of water from the upper to the lower reservoir through hydraulic turbines, while energy is converted into mechanical energy and then to electricity.

5.2. Application

In this work the feasibility of a cumulative capacity of 1000 MW of pumped storage systems in the Greek power system is examined for the three cases of wind–PV integration (3000–500, 5000–1000, 8000–2000 MW). It is assumed that the exploitation of wind power surplus through pumping has been undertaken by a couple of pumped storage plants, each one consisted of several pumps.

The results for two extreme cases of composition A and B, with maximum and minimum flexibility of pumping station are evaluated. The two cases are:

- Case A: Three power plants with pumping stations consisted of 5× 50 MW, 3× 100 MW and 3× 150 MW pumps.
- Case B: One power plant with a pumping station consisted of 3× 333.3 MW pumps.

The above described compositions of pumping stations are examined both for fixed speed pumps and for the case that one of the pumps of each pumping station is variable speed. The part of wind energy surplus that could be exploited for pumping and the degree of utilization of pumping station are calculated and comparably presented in Fig. 6 for the examined cases.

First of all, as regards the option of one variable speed pump, variable speed operation is more flexible and effective, as soon as pumping operation is possible within a range of input power [10]. It is obvious, that one variable speed pump provides operational flexibility, and then a larger part of wind energy surplus is used for pumping and a better utilization of pumping station is achieved. The effect of variable speed pumps is more important in case of composition B. In the composition A, the effect of variable speed pumps plays a secondary role, while the operational flexibility is provided by the larger number and the multifarious sizes of pumps.

As regards the three cases of wind–PV integration examined, the following conclusions are drawn:

- For the scenario I (3000–500 MW) with a rather limited wind and PV integration, the part of wind energy surplus which is used for pumping is very high, but the degree of utilization of pumping station is very low (less than 1%, even for the case with one variable speed pump).
- For the scenario II (5000–1000 MW), which constitutes a moderate scenario, the part of wind energy surplus which is used for pumping varies in the range 63–78% while the degree of utilization of pumping station in the range is still low in the range 4.9–6.1% in the various examined cases.
- For the scenario III (8000–2000 MW), which is the scenario with large scale wind and PV integration the part of wind energy surplus which is used for pumping is fairly reduced (52–60%) due to the fact that in several hours per year the wind power curtailed is much bigger than the rated power of the pumping stations. On the other hand, the degree of utilization is more acceptable in the order of 14.8–17.1%.

Then the first conclusions of this analysis are drawn. The installed capacity of pumped storage systems in the Greek power system should follow the gradual increase of wind and PV installations. A relative high capacity of pumped storage systems, would lead to a very low degree of utilization. On the contrary a relative high capacity of wind and PV systems, without the parallel development of pumped storage systems, would lead to significant amounts of wind energy lost.

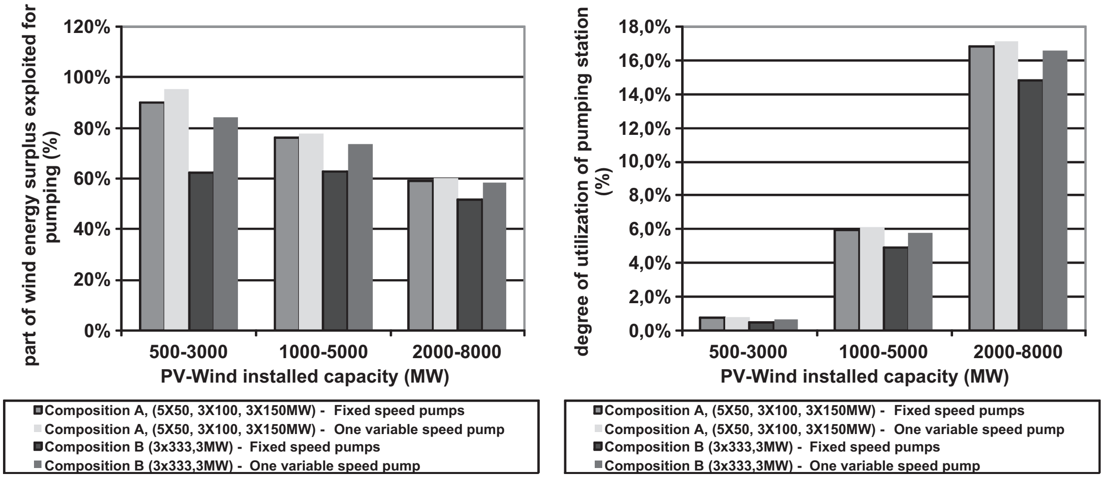

Fig. 6. Percentage of wind energy surplus used for pumping and degree of utilization of the pumping station for the three cases of wind–PV integration, the two cases of pumping station composition and the two cases with fixed speed pumps or one variable speed pump (total 12 cases).

Even in the optimal case (scenario III, with cumulative wind–PV capacity 10,000 MW and 1000 MW pumped storage systems), the degree of utilization of pumping stations remains low in the order of 17%, indicating that such systems could be feasible under special circumstances. One solution could be the complementary use of power from thermal power plants (mainly lignite units) for pumping, in order to improve the degree of utilization of the plant. Pumping operation using exclusively the wind power surplus cannot provide a sufficient utilization of the plants. Additionally, it is obvious that such plants provide to the power grid auxiliary services, which should be quoted properly. Up today these services are provided to the Greek power system from the public power utility and are not paid.

5.3. Tariffs for hydro turbine production

Greek legislation does not provide fixed tariffs for electricity production by pumped storage hydro plants. For the case of pumped storage systems in non-interconnected Greek islands, Law 3658/2006 gives the right to Regulatory Authority of Energy (RAE) to make recommendations to the Ministry who is responsible for the definition of the tariffs. According to this law, these recommendations should be justified by the avoided cost of energy. In Greece, there are many non-interconnected islands. Their classification [2] by their peak demand shows that there are 8 "micro" with less than 1 MW, 11 "small" of the MW-scale, 10 "medium" of the ten-MW-scale and one "large" system (Crete). The spirit of legislator recognizes the difficulty to define fixed tariffs for all these islands, as soon as even in similar sized islands, significant differences occur due to different fuel (heavy fuel oil or diesel), the annual profile of the demand or the individual features of the local power plant.

In the mainland, the avoided cost of energy is rather low with mean annual marginal cost of the order of 60–70 €/MW h, and much higher during the hours of peak demand. In this work, a reverse approach is applied, aiming to define the tariffs for pumped storage hydro turbine production which could provide the feasibility of these plants. This is one of the most critical parameters for the implementation of such plants.

The equalization of the hydro turbines' electricity production cost to the tariff is used as the criterion of marginal feasibility. This means that the required tariff for the promotion of pumped storage should be defined at least to this price.

The hydro turbines' electricity production EPC_T is defined as:

$$EPC_T = \frac{TIC_{PS} \cdot R + OMC_{PS}}{E_T}$$

where TIC_{PS} is the total investment cost of the pumped storage plant, OMC_{PS} the operation and maintenance cost of this plant (including the cost of electricity bought for pumping from wind farms or the grid), and E_T the hydro turbine's energy production.

The annuity factor R is defined as:

$$R = \frac{i}{1 - (1 + i)^{-N}}$$

where, i is the discount rate and N the lifetime of the investment.

This analysis is carried out for the two last scenarios of 5000 and 8000 MW wind capacity, while for lower wind capacity, the pumped storage systems integration is redundant. As regards the cost of electricity which is bought from the grid during the hours of power surplus, it is supposed that this power will be provided from the power system operator to the pumped storage operator, for a rather low price. This price could be related with the marginal cost of electricity in the mainland's power system. In countries with high wind integration, during windy hours of low demand, low marginal electricity cost is modulated [11]. In this connection, the charge of electricity surplus are examined in the range 0–60 €/MW h.

The financial analysis is carried out in the framework of the following assumptions:

- Total investment cost of the pumped storage systems: 2000 €/kW.
- Lifetime of the project: 25 years.
- Discount rate: 6%.
- Efficiency rate of pumped storage procedure: 75%.

It is supposed that the capacity of the reservoirs does not introduce operational constraints and the stored energy is recovered before new wind power surplus is available for pumping.

It is obvious that the required tariff for hydro production depends strongly on the charge of the electricity which is bought from the grid to be used for pumping. This power initially is derived by wind farms in the Greek power system and transmission system operator is responsible to inform pumped storage system's operator about the specific amount of wind energy surplus which is available for pumping. If power surplus from thermal power plants

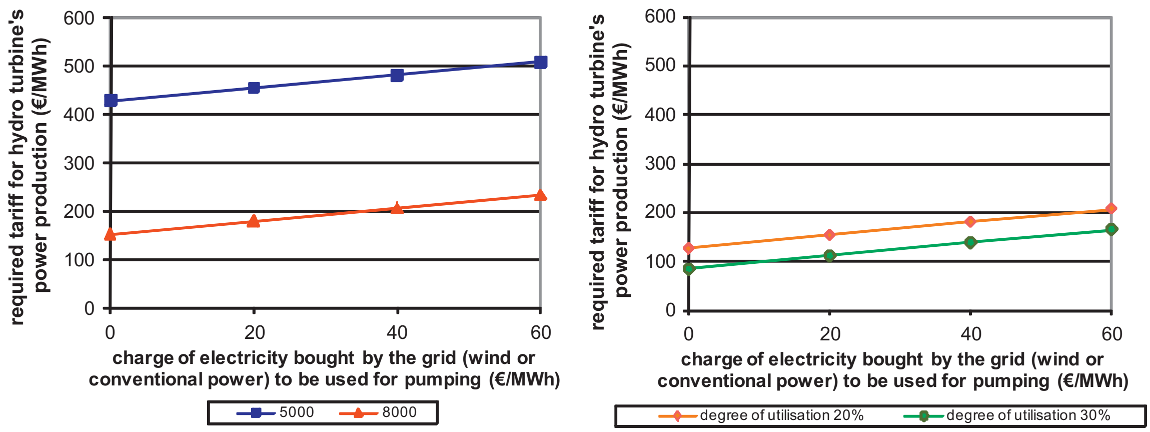

Fig. 7. Required market price for hydro-turbine's energy production (€/MW h) as a function of the charge of grid power for pumping (a) exclusively wind power is used for pumping, (b) complementary conventional power is used for pumping.

is allowed to be used for pumping, again the system operator specifies the available amounts.

Results, show that in case that exclusively wind power surplus is used for pumping, the required price for hydro turbine's production is specified in the range of 430–505 €/MW h for the scenario of 5000 MW and in the range of 150–230 €/MW h for the scenario of 8000 MW (Fig. 7a).

These indicative ranges could be much different in very specific cases that pumped storage systems could be constructed with much lower cost due to topography suitability and exploitation of existing reservoirs. For example, for total investment cost of the order of 1000 €/kW, the two ranges are changed to 210–290 €/MW h for the scenario with 5000 MW and to 75–155 €/MW h for 8000 MW. In all the above ranges the upper value corresponds to the highest examined charge of electricity bought to be used for pumping (60 €/MW h).

With 5000 MW wind installed capacity, wind curtailment is increased and pumped storage starts to have a role in the whole system. Although there is a concrete amount of wind energy curtailed, the shapeless annual distribution, leads to a rather limited financial feasibility of such plants. On the other hand when wind installed capacity reaches 8000 MW, the role of pumped storage systems of 1000 MW becomes very important for the exploitation of wind energy surplus and for the stability of the whole system. With a rather low cost, the variable output of wind energy could be transformed into a predefined renewable power output during the hours of peak demand.

A vicious circle is created; with 5000 MW, pumped storage systems are not feasible, while to reach 8000 MW pumped storage systems are required. The case of use of conventional power for complementary pumping is examined to improve the utilization and the feasibility of the plants.

5.4. *Complementary conventional power for pumping*

In this paragraph, the effect of the complementary power for pumping to the required tariffs is evaluated. Complementary use of conventional power for pumping is permitted to improve the degree of utilization of pumping station. The target is to increase the degree of utilization from 6% and 16.5% in the two scenarios with 5000 and 8000 MW for the case of "A" composition, to 20% and 30% respectively. Then a cumulative daily pumping operation is provided for 4.8–7.2 h. Results are presented in Fig. 7b. In the basic scenario with investment cost of 2000 €/kW, the required price for hydro turbine's production is specified in the range of 205 and 160 €/MW h, for a charge of electricity bought to be used for pumping of 60 €/MW h (same price is considered for wind and conventional power to be used for pumping). For initial investment cost of 1000 €/MW, the required price for hydro turbine's production is specified in the range 145 and 120 €/MW h. Here, lower prices correspond to lower degree of utilization. Prices are common for the two scenarios of wind capacity due to similar degree of utilization.

Using conventional power for complementary pumping, the required price for hydro turbine's power production is estimated in the same order with the marginal cost of the system during the hours of peak demand, proving that pumped storage concepts could take advantage of the difference of the marginal cost between hours of low and peak demand and could be a competitive solution.

6. Conclusions and discussion

As it follows from the above analysis is needed flexibility of the pumping station, or even better the combined use of at least one variable speed pump in each project. At the same time, it is useful to permit complementary use of conventional power for pumping, especially at that transitional stage between 5000 MW and 8000 MW wind capacity in the Greek system. The setting of tariffs for the power for pumping and for power output of hydro-turbine should be defined in the framework of a complete study which takes into consideration the cost of these plants, but also sets the maximum permitted contribution of conventional power for pumping and the pricing of the guaranteed power and the auxiliary services. Certainly the definition of the tariffs is required to reduce the uncertainty of these projects. Additionally, the operator of the electrical system must play a central role in the operation of the pumped storage systems. The morphology of the Greek terrain and the existence of hydro plants with large reservoirs in the mainland, allows the construction of reverse hydroelectric plants or the modifications of the existing plants to reverse plants. These projects may require considerable time for both the authorization and for its construction, and given the undeniable their operational feasibility, should immediately be integrated into national energy planning. Finally, a predefined schedule of wind farms implementation is required, because the operation of pumped storage systems depends on wind power surplus.

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